

Synchrotron Radiation and Quantum Gravity

John Ellis,

CERN, Theory Division, CH-1211 Geneva 23, Switzerland;

N.E. Mavromatos,

Department of Physics, King's College London, University of London, Strand, London WC2R 2LS, U.K. and Departamento de Física Teórica, Universidad de Valencia, E-46100, Burjassot, Valencia, Spain;

D.V. Nanopoulos,

George P. and Cynthia W. Mitchell Institute for Fundamental Physics, Texas A&M University, College Station, TX 77843, USA, Astroparticle Physics Group, Houston Advanced Research Center (HARC), Mitchell Campus, Woodlands, TX 77381, USA and Academy of Athens, Division of Natural Sciences, 28 Panepistimiou Avenue, Athens 10679, Greece;

A.S. Sakharov,

CERN, Theory Division, CH-1211 Geneva 23, Switzerland and Swiss Institute of Technology, ETH-Zürich, 8093 Zürich, Switzerland.

Quantum Gravity may cause the vacuum to act as a non-trivial medium (space-time foam) which alters the standard Lorentz relation between the energy and momentum of matter particles, thus modifying their dispersion relations. In an interesting recent Nature paper, Jacobson, Liberati and Mattingly [1] have argued that synchrotron radiation from the Crab Nebula imposes a stringent constraint on any modification of the dispersion relation of the *electron* that might be induced by quantum gravity, but their analysis does not constrain any modification of the dispersion relation of the *photon* of the type first proposed in [2, 3]. Such quantum-gravity effects need not obey the equivalence principle [4] in the sense of being universal for all matter particles, as exemplified by quantum-gravity models in which photons are the only Standard Model particles able to ‘see’ special quantum-gravity configurations that modify their dispersion relations. This implies that photons may be the only sensitive probe of quantum-gravity effects on particle dispersion relations, and the results of [1] *do not* exclude all possible modifications of dispersion relations, even if they are suppressed by only a single power of the Planck mass (the characteristic quantum-gravity scale), contrary to the stronger interpretation of the results of [1] given in some subsequent commentaries in the scientific press.

As was pointed out in a preprint [4] released shortly before the publication of [1], there are theoretical models in which quantum gravity produces Lorentz invariance-violating effects for neutral particles, like the photon, but not charged particles,

like the electron. One model of space-time foam [3] suggests a linear modification of the dispersion relation for the photon: $p_\gamma = E_\gamma - (E_\gamma^2/M_{QG})$, where p_γ (E_γ) is the photon's momentum (energy) and M_{QG} is some characteristic scale associated with quantum gravity, which may be of the same order as the Planck Mass $M_P \sim 10^{19}$ GeV. However, the model [3] predicts that there is *no such modification* of the dispersion relation for the electron [4], and hence is compatible with the constraint [1] from the Crab Nebula. In such models, constraints on the electron and nucleon dispersion relations [1, 5, 6] are irrelevant, leaving measurements on time profiles of very remote gamma-ray bursts [2, 7] as the best approach for probing quantum-gravity effects.

The basic reason for this violation of the equivalence principle in the quantum-gravity model of [3] is its description of space-time foam via quantum defects in space-time with vacuum quantum numbers, as appear in a certain interpretation of Liouville string theory [8]. These can be excited only by particles that are *neutral* under the gauge group of the Standard Model, such as *photons*, and such interactions give the vacuum a non-trivial refractive index for light of different frequencies (energies) [2]. *Charged* particles, such as *electrons*, cannot form such excitations, so do not ‘see’ the space-time foam at all, and hence obey the usual Lorentz kinematics. As a result of the excitation of the vacuum by an energetic photon, space-time is distorted, and the photon travels with a velocity smaller than the (supposedly universal) speed of light *in vacuo* c , as postulated in the special and general theories of relativity.

Since the electron has *no* interaction with the quantum-gravitational vacuum medium in this approach, it emits no Čerenkov radiation, despite travelling faster than photons, thus avoiding the vacuum Čerenkov radiation constraint considered in [9], as well as the Crab Nebula constraint derived in [1]. The model of [3] also avoids the strong constraints in [10] and many other constraints on quantum-gravity effects [11]. Moreover, recent claims that modified dispersion relations for photons would result in phase incoherence of light and thereby destroy diffraction patterns in images of extragalactic sources [12] have been criticized in [13], where it was pointed out that [12] overestimated the induced incoherent effects by a large factor. In the specific model [3], the re-emission of the photon by a space-time defect is accompanied by a *random* phase in its wave function, destroying any cumulative phase incoherence. Finally, we note that, since the nucleon is a bound state, it is more complex to analyze, but we also do not expect it to exhibit a linear modification of the normal Lorentz-invariant dispersion relation, avoiding other constraints [5, 6].

The strong bound of [1] on the electron serves to underline the interest in probing directly the dispersion relation of the photon. The study of the arrival times of

photons from gamma-ray bursts [2] still appears to be the best experimental probe of any possible refractive index for photons, and should be pursued further in the future. It has already established a lower limit on M_{QG} close to 10^{16} GeV [7], and current (HETE, INTEGRAL) and future (GLAST, AMS) high-energy space missions have the potential to reach the Planck scale for any linear quantum-gravity modification of the photon's dispersion relation.

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